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PHYSICAL PRINCIPLES OF ELECTRIC-SPARK METAL-WORKING

B. R. Lazarenko, Doctor of Technical Sciences

Every year more and more investigators devote themselves to the study of the phenomena accompanying the passage of an electric current through a gas in initial state at normal temperature and pressure. In addition to using steady-state electrical processes, the phenomena accompanying nonsteady forms of electrical discharge in gases and liquid, electric-spark discharges in particular, are subjected to intense study.

From the results of these investigations a new branch of technology originated and is being successfully developed. It is called electric-spark metal-working and is based on the use of the phenomenon of electrical erosion of metals in a pulsed discharge.

An electric-spark discharge occurs only at very high electrical-field strengths, lasts only 10^{-3} sec or less and is characterized by a falling volt-ampere characteristic. The resistance of the spark channel varies according to a nonlinear law, thus causing the rate of buildup of the current in the circuit to fluctuate from 10^4 to 10^8 amp/sec. The amplitude values of the current and the power outputs that can be achieved in an electric-spark discharge cannot be obtained by any other methods. The temperature in the spark channel is close to the temperature of the sun.

The fissioning action of the pulse is so great that all the chemical elements

contained both in the interelectrode medium and in the electrodes produce an atomic spectrum. The place of application of the pulse is always strictly localized on both electrodes. In an electric-spark discharge the material of the anode, in the overwhelming majority of cases, is more intensively consumed.

If the anode is a very thin conductor of current, e.g., a metal foil, a beam of electrons striking its surface pierces it easily and continues its path in the transanodic region. In this case the anode plays the role of a peculiar accelerating grid. Only a very small quantity of energy is expended on the breakdown of a thin anode. Consequently, the electron beam, although moving in the transanodic region, still possesses a very large energy reserve. Therefore, when it encounters any substance whatever in its path, the electron beam, by striking it, will produce considerable work.

If the anode is a fairly thick metal plate (albeit only several millimeters thick), a beam of moving electrons will be abruptly stopped by the solid metal surface. In this case all the deceleration energy of the electrons is liberated in the surface layers of the anode. Since the power output in this case is fairly high, a directed explosion of the section of the anode receiving the pulse occurs. During the time of the electrical explosion all the molten metal, as well as all the softened metal, is ejected out of the beaker containing the damaged volume of metal. It is precisely this phenomenon that is used in industry.

From the time of our first publication concerning the discovery of this method* great attention has been given to its development not only by scientists of the USSR, but also by investigators and industrialists abroad (e.g., a special institute was created in Japan).

Among foreign scientists various points of view developed concerning the mechanism of the metal-ejecting processes occurring as a result of the action of

* B. R. Lazarenko and N. I. Lazarenko. Electrical Erosion of Metals. Gosenergoizdat, 1944.

a spark pulse.

One group (V. M. Williams, USA et al.) starts from the premise that a discrete portion of metal is separated from the entire mass of metal as a result of the action of the electrical-field forces and that in this case the detached particle does not even melt. According to Williams, the forces detaching the particle from the mass of metal develop as a result of the extraordinarily high current density in the point zone of the surface of the material being worked and, consequently, from the high potential gradient and the field force on the positive ions of the crystal lattice. The magnitude of the electrical-field forces is estimated by the author from the depth and area of the crater which forms, as well as from the magnitude of the discharge current. Williams claims to have obtained quantitative ratios which are in fairly satisfactory agreement with the experimental data.

The supporters of another theory attribute the mechanism of electric-spark working to the occurrence of mechanical forces. For example, N. Mironov and I. Pfau (Switzerland) assume that in the case of an electric-current spark pulse it is difficult to speak of a measurable temperature or of a thermal effect in the ordinary sense of the word, since everything happens instantaneously and in too concentrated a fashion. In their opinion, it is more accurate to call this process a "hyperthermic shock", since we are dealing with an extremely localized mechanical action, which shakes the metal with such force that it causes a tearing away, an explosion or freeing of the metal particles, before thermal propagation of the discharge can take place on the lower layers of the metal.

We shall not evaluate all the theories explaining the mechanism of ejection of metal by electric-current spark pulses but shall just make certain remarks concerning the assertion of Williams that during a spark pulse the material is torn off without melting. This assertion contradicts an overwhelming number of experimental data. The products of electric-spark erosion always have a spherical

shape and are actually solidified drops, which can readily be proved by any method. Powder-metallurgical and very brittle materials constitute an exception to this general rule. They simply disintegrate under the action of a current pulse. Williams conducted tests on one of these materials — tungsten carbide.

The largest group consists of those foreign scientists who share our views concerning the physical phenomena occurring in the interelectrode space and on the electrodes during the passage of a spark pulse. Utilizing the most recent achievements of measurement technology, we were able to describe a whole complex of basic characteristics of an electric-spark discharge in a gas or liquid dielectric and to construct a model of the process of ejection of metal by a spark pulse of an electric current in such a way that it agreed fairly well with the experimental data.

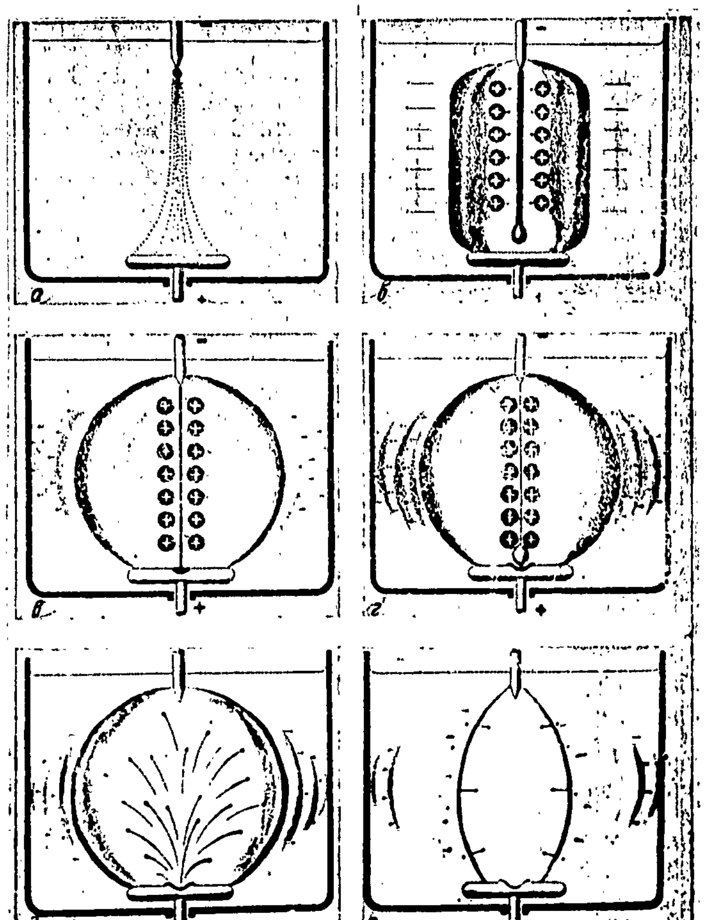

Fig. 1. Diagram of the passage of an electric current through a liquid dielectric.

First of all, it was established that the passage of an electrical pulse is accomplished in two phases. The first of these phases — the preparatory phase — lasts from 10^{-7} to 10^{-8} sec and consists of ionization of the dielectric located between the electrodes and formation of the through-conduction channel. The second phase consists of the transmission, with the aid of this channel, of the energy stored in the system.

The mechanism of the passage of an electric current through a liquid dielectric begins as a result of the fact that during buildup of the electrical field the particles suspended in the liquid are drawn by the action of the field into the region of maximum intensity (Fig. 1a).

When the electrical-field strength reaches the required magnitude, a streamer detaches itself from the cathode and heads for the anode through the particles suspended in the liquid, evaporating and ionizing the liquid in its path. The electron beam, moving behind the streamer, is subjected to the radial compressive force of the ions, which decrease its cross section and guide its movement, i.e., as a result of the action of the electronic-optical phenomena the moving electron beam is "unwound" from the surrounding space (Fig. 1b).

Thus at the moment the streamer approaches the anode the working volume of the liquid is rent asunder. The resulting space contains steam, gas, plasma and the electron beam (the investigation proceeds from the walls of the vessel containing the liquid to the discharge axis). The temperature gradient is very high (of the order of $10,000^{\circ}$). The forces arising in the case of the liquid, steam and gas are directed away from the discharge, while those arising in the case of the plasma and the electron beam are directed towards the discharge axis. Since the formation of these processes in the interelectrode space takes 10^{-7} to 10^{-8} sec and, consequently, is of explosive character, a shock wave arises and begins to propagate in the liquid (in the plane perpendicular to the discharge axis).

When the streamer reaches the anode, the through-conduction channel forms, and through this channel the electrical system, with a spurt, liberates the energy which it has stored up. At the same time enormous forces are liberated in very small working volumes. The current pulse, traversing the interelectrode space, causes the appearance of an extremely strong magnetic field. As a result of the action of the electrodynamic forces which arise the ions begin to move towards the discharge axis at high velocities. A consequence of this directed motion is the compression of the electron beam (so-called pinch effect) shown in Fig. 1c and the very sudden increase in the temperature of the current-conducting channel (a phenomenon recently established as a result of work done under the direction of Academician L. A. Artsimovich).

The surface of the anode receiving the current pulse undergoes a number of important transformations. The impact of the electron beam on the hard and cold metallic surface causes mechanical rupture of the crystals in the metal. As a result of the fact that the length of the entire process of the passage of the electric current is very small, the electron beam is able to melt and bring to a very high temperature a certain volume of the anode. Since in this case the current densities reach a value considerably exceeding the value at which the mechanism of conduction by free electrons operates, the electro-dynamic forces eject into the interelectrode space all the melted and softened volume of metal (Fig. 1d). (It is known that if an electric current exceeding a certain critical value flows through a metallic conductor, its passage always involves selective removal of the material of the conductor).

Since the passage of the current is not yet complete, the strongly heated bottom of the anode beaker, from which the metal is ejected, enters into a chemical reaction with the extremely hot plasma. The new chemical compounds that form diffuse deep into the anode under the action of the current. The drop detaching itself from the anode is accelerated, enters the zone of very high

temperature, begins to boil and bursts. However, at this moment the electrical circuit is broken and, consequently, the passage of the electric current ceases in the interelectrode space (Fig. 1e). Obviously at this moment the liquid adjacent to the gas space also reaches its maximum value; vapor and drops of exploded metal are flying around in the gas space; the surface of the beaker on the anode is heated to a temperature close to the boiling point.

At the next moment, since the passage of the electric current in the interelectrode space has ceased, deionization and destruction of the gas space will begin (Fig. 1f). Since the hydraulic shock wave was directed away from the center of the discharge, in the final phase of the process explosions of the liquid can occur. Vapor and drops of flying metal, landing in the liquid, will cool and fall to the bottom of the vessel. Since surface-tension forces are acting in this case, the solid forming during cooling must have a minimum surface. Consequently, all the fractions of the dispersed particles will assume a spherical shape. Due to the fact that the strongly heated bottom of the bowl thus formed is surrounded by a large mass of cold metal and is washed by cold liquid, very rapid cooling of the metal surface will take place, thus leading to a change in the structure of the metal.

It is thus that the complex process of the passage of an electric-current spark pulse through a liquid can be described in the first approximation.

More than fifteen years ago we stated that there are no materials, nor can there be any, which are capable of withstanding the action of an electrical pulse. During the entire intervening period none of the investigators working in this field was able to establish even one exception to this rule.

The initial physicochemical properties of the working electrodes are considerably changed. Metallographic, chemical, spectrographic and X-ray diffraction measurements identically establish that every time the metal receives spark pulses new chemical elements, new phases, appear in its composition. The

slime forming as a result of the action of spark pulses always consists of metal powder from the electrodes and a certain quantity of carbon black if the pulse occurred in a liquid medium containing carbon. The size of the particles forming can vary from colloidal dimensions to spheres several millimeters in diameter. The largest of them are often found in the interior of the cavity.

The force of the hydraulic shock that occurs is such that during the passage of a pulse in closed vessels containing small volumes of liquid these vessels burst, even if they are made of strong steel. In the case of large volumes of liquid (of the order of many liters), due to the comparatively low propagation velocity of the shock wave and the appearance of the process of negative pressure in the final phase, the strength of comparatively thin metal walls is already sufficient for the reception of the wave thus formed, so that only a vibration of the walls of the vessel occurs.

All the processes considered are valid only for electric-current spark pulses. As soon as the duration of the pulses exceeds the above-mentioned limit (10^{-3} sec), electric-arc pulses appear, and the picture of the processes changes abruptly. The most serious consequence is the disruption of the self-focusing of the discharge; it "crawls apart" along the surface of the anode. Moreover, the beginning of the intense action of the ion processes causes the surface of the electrode to be heated so strongly that it melts. Hence it is clear that in order to carry out, for example, dimensional working of metals, only the spark form of an electrical discharge is suitable, and the possibility of the appearance of the arc form must be eliminated.

Deserving of attention are certain quantitative relationships characterizing electric-spark erosion of metals. It has been established by experiments that electrical-energy pulses with the same characteristics are capable, all other conditions being equal, of ejecting from the anode different quantities of metal, depending on the chemical composition of the metal. Comparative data concerning

the number of pulses required for the ejection of 1 cm^3 of anode material are given in the following table.

Anode material	Total number of pulses	Anode material	Total number of pulses
Tin	8,064	Copper-graphite composition, type MG-2	52,800
Bismuth	8,316	Nickel	63,210
Lead	8,484	Steel Kh12M (red hot)	71,190
Cadmium	8,736	Iron	102,270
Aluminum	9,240	Molybdenum	125,580
Zinc	9,786	Graphite	191,520
Brass LS-59	41,580		
Copper	52,500		

A change in the pulse parameters will cause a change in the total number of pulses required for the ejection of 1 cm^3 of anode material, but will not change the order in which the materials are arranged in the table.

It has been shown experimentally that if we take pulses with identical energy, the quantity of material ejected by them depends with mathematical accuracy on the total number of pulses and is determined very accurately by the equation:

$$\gamma = kEn,$$

where γ is the quantity of ejected material in g/sec or cm^3/sec, E is the energy of a single pulse in w/sec, n is the pulse frequency in sec, and k is a proportionality factor determined by the physical constants of the electrode material, by the composition of the medium and by the length of the pulse.

The cycle of operation of an electrical system generating spark pulse can be expressed in the first approximation by the following equation $T = t_p + t_f + t_o + t_r$ where T is the total time of the cycle, t_p is the preparatory time, during which the system accumulates energy, t_f is the formation time of the through-conductance channel, t_o is the actual operating time, when the system gives up its accumulated energy, thereby causing material to be ejected from the electrodes, and t_r is the time during which the medium restores its electrical strength.

The spark can be characterized analytically by a rectangular current pulse with a time length t. Consequently, the energy of the spark W can be calculated from the formula:

$$W = \int_0^t P_c dt = P_c t \,[\text{дж}],$$

where P_c is the instantaneous power.

A chain of sparks succeeding each other through constant intervals of time T, under the condition that $T \gg t$, will give rise to an average power

$$P_m = Wf = \frac{W}{T} = \frac{P_c t}{T}.$$

This equation corresponds to a wave of rectangular current pulses with a repitition rate $f = \frac{1}{T}$.

Since T is several orders greater than t, a simple calculation shows that a pulse wave with an average power of only 10 w will cause a solitary-pulse impact with a power of many kilowatts.

The electric-spark method of working metals, based on the use of the phenomena accompanying the pulsed liberation of electrical energy in a discharge gap, is easy to control. With the aid of this very powerful technique it becomes possible to work any electrically conducting material regardless of its physicochemical properties (hardness, viscosity, melting point, chemical composition, etc.) without using an instrument made of harder material. The working elect[illegible]e is usually made of brass, cast or uncast iron, graphite, or aluminum. No c[illegible]ting instrument (cutters, drills, milling cutters, broaches, abrasives, etc.) is required in this case.

Pulsed generation of energy in the working zone enables us to perform, with an equal degree of success, such operations as the cutting of metals, making holes of any shape and dimensions in them, grinding, applying coatings, changing the structure of the surface, etc. With the aid of the electric-spark method it is possible to carry out a number of technological processes absolutely unfeasible by any other methods,

e.g., making non-circular openings with curvilinear axes, making objects with a wall thickness of several tens of microns, etc. The economic efficiency of all these processes is very high.

In accordance with the new, electrical method of metal removal the structure of the "machine" with the aid of which the treatment is accomplished also changes. There is no longer any need for all the basic components transmitting the mechanical forces involved in the concept of a metal-working machine. The main working organ of the apparatus for electric-spark working is an electrical-energy pulse source, which generates current pulses with given time and power characteristics. The kinematic part of the apparatus becomes an auxiliary element.

Since electric-spark metal-working is an electrical process, its complete automation presents no great complexity. Automatic electric-spark apparatuses have been produced and are already operating in industry. Some of these apparatuses operate according to a preassigned program.

In conclusion, it should be noted that from our point of view electric-spark metal-working is remarkable not only for the fact that it made possible a reduction in the volume of work formerly done by mechanical cutting, nor even for the fact that a number of new progressive technological processes appeared. The most remarkable thing is that from now on the designer, the creator of new machines, is freed from the burdensome necessity of constantly reckoning with the capricious requirements of technologists with respect to the workability of materials. Now the designer can take any material and specify in essence any process of dimensional working. An electric spark will rapidly and precisely realize all his intentions.

The fast tempo of development of electric-spark metal-working is to a considerable degree facilitated by the fact that the Central Scientific Research Laboratory of Electrical Working of Materials of the Academy of Sciences of the USSR, in which the most extensive work in this field is concentrated, constantly coordinates its activity not only with related laboratories in our country

existing in the Academies of Sciences of the autonomous republics of the USSR and in industry, but also with analogous foreign organizations (the Academies of Sciences of Czechoslovakia, China, etc.).

In spite of the considerable development of electric-spark metal-working, specialists in this new field are well aware that only initial achievements have been made and that in the very near future new, even more remarkable processes based on pulsed liberation of electrical energy will appear.

This assertion is based, firstly, on the fact that the technological possibilities of the electric-spark method of metal-working are far from being exhausted. The boundaries of application of this process will always expand. In the second place, the reliability of the information obtained concerning the physical picture of the processes accompanying pulsed liberation of electrical energy enabled investigators working in this field to considerably expand the boundaries of application of short electric-current pulses and to pass from the problem of working current-conducting materials (metals and their alloys) to the solution of the problem of dimensional working of semiconductors and insulators. Moreover, the extremely high power characteristics of short electric-current pulses give us reason to assume that they should, without question, also be used in carrying out various chemical and biological investigations.

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